Modeling Surfzone/Inner-shelf Exchange

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LONG-TERM GOALS

The exchange of tracer (contaminants, pathogens, sediment, or larvae) between the surfzone and the inner-shelf, important to Navy operations, is poorly understood. Breaking-wave driven surfzone processes are radically different from the wind, stratification, (non-breaking) wave, and rotation driven processes in the inner-shelf. The time-scales of the processes is also quite different in these two regions. The interaction of these processes governs this exchange, and depends on the waves, wind, tide, and stratification. The long-term goal is to understand the processes that drive cross-shore exchange across both the surfzone and inner-shelf and figure out how to model them accurately.

OBJECTIVES

The time-scales exchange of the processes in the surfzone (< 10 min) and inner-shelf (hours+) are quite different. The interaction of these processes governs this exchange, and depends on the waves, wind, tide, and stratification. To study exchange between the surfzone and inner-shelf, the specific objectives are to:

1. Develop a model appropriate for studying surfzone/inner-shelf exchange by coupling the wave-resolving surfzone model `funwaveC` and ROMS. `funwaveC` has been validated for surfzone waves, currents, drifter and tracer dispersion, and runup. Finite-crest length wave breaking is incorporated into the model and thus it resolves rip current forcing mechanisms. The wave-averaged ROMS model (appropriate for the inner-shelf and some surfzone applications) incorporates all the inner-shelf exchange mechanisms, including those that are wave-induced. Two potential coupling paths will be explored.

2. Test and calibrate the model with coupled surfzone & inner-shelf observations from the ONR funded HB06 & IB09 experiments led by the PI. Both experiments had significant surfzone and inner-shelf dye, temperature, wave, current, and turbulence observations with which to compare to the coupled surfzone-inner shelf model. The observations of dye, temperature, and current vertical structure from the outer surfzone to inner-shelf will provide a *challenging* test for the model.

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3. Use the model to diagnose mechanisms of tracer exchange and determine their importance given different incident wave, wind, stratification, tide, and coriolis conditions that would be appropriate for various regions in the world of interest to the Navy. This work will quantitatively improve out ability to make predictions of the fate of pollutants and contaminants, in addition to other tracers, in the nearshore region

APPROACH

Tasks 1 and 2 have had significant progress. Note that this is work was performed as a collaboration between the PI and postdoctoral researcher Nirnimesh Kumar.

Task 1. Parameterizing Wave-Resolving Small-Scale Vorticity Generation

The goal here is the use a wave-resolving Boussinesq model to figure out how to parameterize the vorticity generation due to short-crested breaking of individual waves. The Boussinesq model `funwaveC` used here, developed by the PI and distributed as open-source software, has been validated in ONR funded studies for surfzone waves, mean currents, and surfzone eddies [*Feddersen et al.*, 2011], surfzone drifter dispersion [*Spydell and Feddersen*, 2009], surfzone dye dispersion [*Clark et al.*, 2011], and shoreline runup [*Guza and Feddersen*, 2012]. Of particular relevance to surfzone/inner-shelf exchange, is the ability to model surfzone tracer dispersion accurately. The `funwaveC` model includes the physics of vertical vorticity injected into the surfzone by breaking waves, which evolves into a statistical distribution of surfzone eddies that stir and mix tracer. This model is run in a variety of configurations to isolate the vorticity generation by individual breaking wave events, and quantify its spatial and temporal evolution.

Task 2. Testing the Model with Coupled Inner-shelf and Surfzone Observations from HB06

The PI led the recent surfzone and inner-shelf dye transport and fate field experiment called HB06 funded by ONR. HB06 took place at Huntington Beach Ca in fall 2006 and had significant surfzone and inner-shelf dye, temperature, wave, and current observations with which to compare to the coupled surfzone-inner shelf model and examine the processes of SZ/IS exchange. A cross-shore tripod and mooring array, spanning 4 km, was deployed to measure waves currents and temperature over 2 months over the late summer to fall transitional break-down of stratification. These long time-series [*Wong et al.*, 2012; *Nam and Send*, 2011; *Omand et al.*, 2012], spanning near-shoreline to 27 m depth, are ideal observations with which to test the combined IS/SZ model and it's ability to reproduce waves, currents, and observations.

The COAWST model (coupled ROMS/SWAN) is run for 3 months during the HB06 experiment at Huntington Beach held in Aug-Oct 2006. Certain model details include. The number of grid points in cross and alongshore directions is 574 (x) and 304 (y). The number of vertical levels is 20, and the horizontal grid resolution is 35 m. The turbulence closure scheme is k-ϵ.

At all the offshore boundaries, time series of sea surface elevation, barotropic and baroclinic velocities, and tracers (temperature and salinity) is provided with a temporal resolution of 2 hours. These boundary conditions have been obtained from simulations conducted by Yuske Uchiyama and Jim McWilliams at UCLA and are denoted UCLA ROMS. Wind forcing and net surface heat

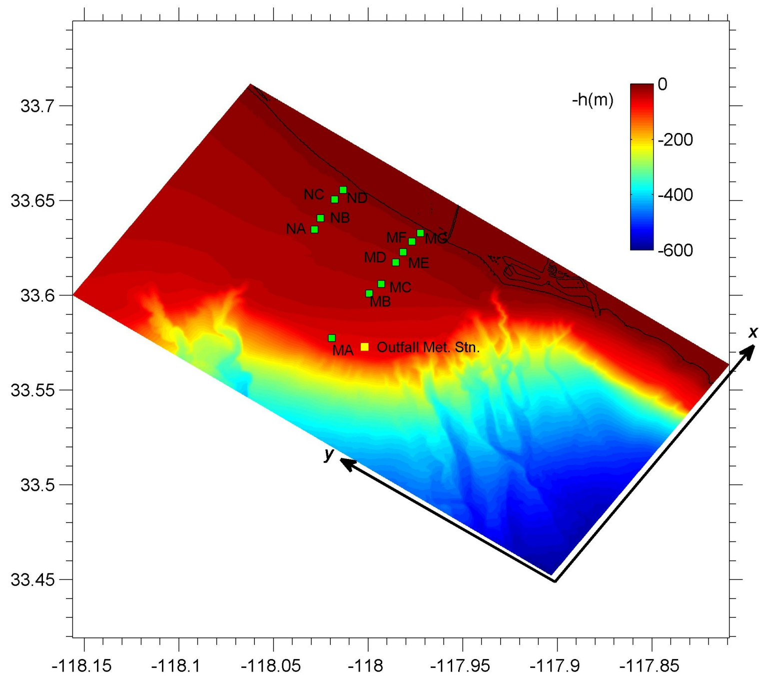

Figure 1: Color shading of bottom bathymetry, mooring locations (green squares) and the local co-ordinate system (black arrows). Positive *x* is directed towards the northeast (cross-shore), while positive *y* points to the northwest (alongshore). Text represents the mooring ID used in this study.

flux during the simulation period are obtained from a 6 km resolution Weather Research Forecasting (WRF) simulation (see U13), while boundary condition for sea surface temperature and salinity are obtained from AVHRR based climatology for the study area.

The model prognostic variables (sea surface elevation, alongshore and cross-shore velocity, and sea surface temperature) are compared to measurement of hydrodynamic parameters for a period of ~ 3 months. Fig. 1 shows the ID and location of moorings along with the co-ordinate system used in this study is shown.

WORK COMPLETED This effort began in March of 2013. Since then, the following tasks have been completed.

- The appropriate manner to non-dimensionalize the breaking wave vorticity forcing has been derived.
- A variety of Boussinesq model simulations of breaking wave events have been performed.
- Individual breaking wave events have been isolated and their parameterized form studied.
- Numerical simulations of the HB06 region have been performed with a coarse (35 m) grid spacing, and analyzed.
- Wave boundary conditions have been generated from CDIP wave model information.

- A SWAN-only simulation has been performed for the entire region and validated.
- Finer (9 m) grid size simulations are running.
- We have applied for DoD supercomuter time.

RESULTS

Task 1. Parameterizing Wave-Resolving Small-Scale Vorticity Generation for use in COAWST-ROMS

As a next step in this analysis, we focus on quantifying an individual wave breaking event. We take inspiration from [*Sullivan et al.*, 2007], who parameterized the effects of individual wave breaking in a LES model of the ocean mixed layer. Here, the idea is to use `funwaveC` to parameterize the vorticity variability forcing terms and then stochastically insert them into the a ROMS model that includes the surfzone. As ROMS is a primitive equation model, vertically integrated it is simply the shallow water equations. Thus, the generated eddies would be able to evolve according to 2D turbulence. The wave forcing vector due to an individual breaking wave is represented as $\mathbf{F}$, which can be divided into an irrotational scalar (ϕ_F) and a rotational vector quantity (ψ_F) such that

$$\mathbf{F} = -\nabla\phi_F + \nabla \times \psi_F$$

where the rotational part of the wave forcing is the part that has a non-zero curl, ie,

$$\nabla \times \mathbf{F} = -\nabla^2\psi_F \tag{1}$$

If we can parameterize the breaking wave forcing events via ψ_F, then, similar to [*Sullivan et al.*, 2007], these events can be inserted stochastically into ROMS.

Figure 2 is an example of the application of this decomposition to a single wave breaking event. Simulations were conducted for an alongshore uniform beach, with the cross-shore profile representative of the HB06 beach profile. At the offshore boundary two wave trains with same amplitude and frequency, but different angle of incidence are allowed to propagate towards the shoreline, thus creating regions of constructive and destructive interference. The consistent group pattern begins to generate rip currents. The wave breaking (see normalized eddy viscosities), forces non-zero $\nabla \times \mathbf{F}$. This can be isolated by solving (1) to get ψ_F (right panel). We are now non-dimensionalizing these ψ_F and figuring out how to parameterize their spatial and temporal variability.

Task 2. Testing the Model with Coupled Inner-shelf and Surfzone Observations from HB06

Alongshore flows simulated by the coarse UCLA ROMS model and COAWST show similar temporal variability (to each other). Measured and modeled subtidal (33 hour low pass filtered) flows are compared in the mid-water column at all mooring locations. Mean and standard deviation of measured and modeled alongshore/cross-shore flows are compared (eg., Figure 3). Modeled estimates of mean cross-shore velocity has similar vertical distribution at most of the mooring locations except site MD (not shown). On the contrary, the model estimated standard deviation of

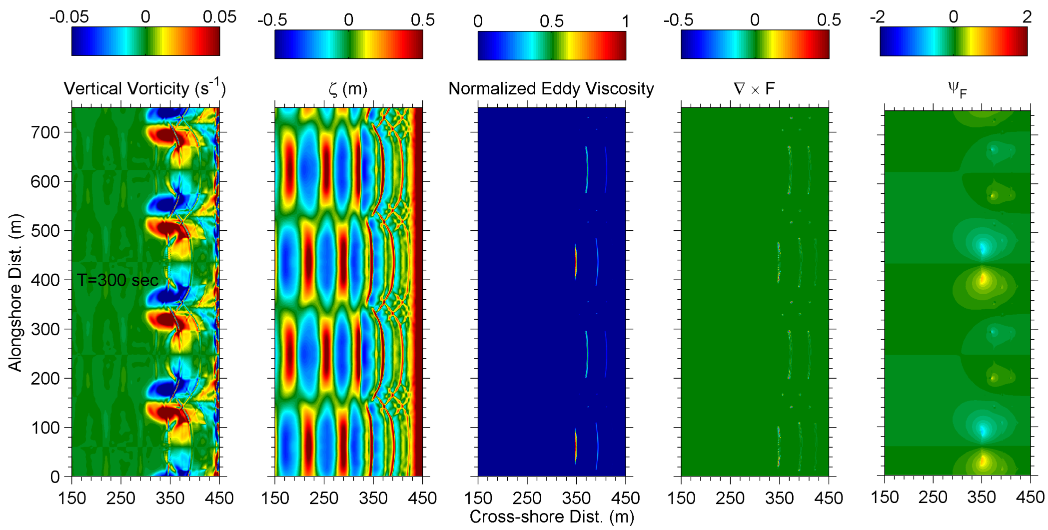

Figure 2: Maps of (left to right) vorticity, sea-surface elevation η, breaking-eddy viscosity, forcing of vorticity $\nabla \times \mathbf{F}$, and forcing streamfunction ψ_F as a function of cross-shore coordinate x and alongshore coordinate y.

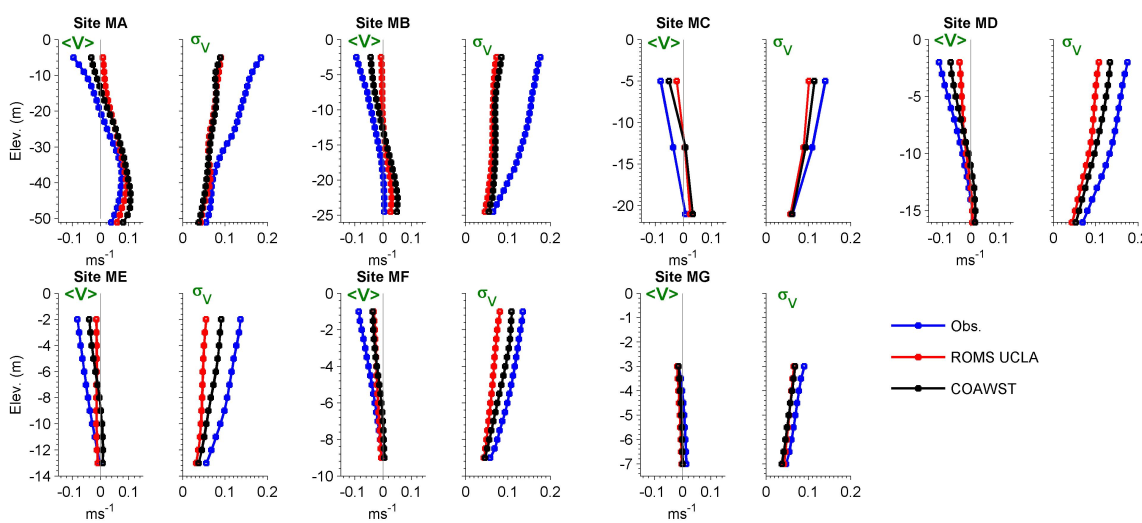

Figure 3: Mean($\langle v \rangle$) and standard deviation σ_v of vertical distribution of alongshore velocities at sites MA, MB, MC, MD, ME, MF and MG calculated using observed (blue) and simulated UCLA (red) and COAWST (black) results.

cross-shore flow is usually smaller than measurements at all water depths. Model simulated mean and standard deviation of alongshore flows is usually smaller than the observations. In addition, the measured flows have stronger vertical shear in comparison to simulated flows.

Vertical profile of measured and simulated temperature means and variances at sites MA, MB and ME are shown in Figure 4. At all mooring locations, model temperature is warmer than observations at the start of the simulation (4). ROMS UCLA and COAWST only have slight difference in temperature profile variability as a function of time. Observed temperature is usually cooler close to the sea-bed and warmer at the surface in comparison to modeled temperature. This trend is valid from the deepest mooring location (MA, Figure 4) to shallower waters (ME, Figure 4). Time series of difference in temperature measured close to the sea surface and the seabed at a mooring location (not shown) is compared to model results obtained from similar analysis. Modeled difference in temperature is substantially less in comparison to observed differences. Also this weakness in modeled vertical temperature gradient is more pronounced for offshore locations (e.g., site MA) in comparison to locations farther inshore. Standard deviation of measured temperature is always more than those obtained from model results. This difference reveals that oscillation in temperature signal due to tidal variability is stronger for measurements in comparison to the model. Also the mean temperature in deeper waters can be 4-5^oC cooler than modeled mean temperature. Nevertheless, the vertical distribution of these quantities modeled by ROMS UCLA and COAWST is similar to those observed.

Finally, the depth-integrated heat content (H) at any mooring location is calculated as

$$H = \rho \cdot C_p \cdot \int_{-z_{bot}}^{-z_{top}} T \cdot dz$$

, where ρ is the water density and C_p is the heat capacity of water. This calculation is conducted for water depths corresponding to the vertical extent of mooring temperature measurements. At site MF, low pass filtered HC from modeled temperature is higher than those observed. This finding is consistent with the fact that initial model temperatures are higher than those observed. However, the modeled HC shows similar variability to observations.

Lastly, SWAN-only wave simulations have been performed to test the wave model grid and boundary conditions. Comparisons have been performed with both a wave buoy deployed in 22-m water depth and with the cross-shore array of surfzone tripods. A comparison of model and observed wave conditions at the 22-m depth buoy is shown in Figure 5. In general, the wave field is quite well simulated.

IMPACT/APPLICATIONS

This work will have significant impact as it will allow for a *single* model to be used to study exchange processes from the surfzone to the shelf-break.

RELATED PROJECTS

This project is directly related to the postponed ONR DRI titled: *The Inner Shelf Connecting the Coastal Ocean and the Surf Zone* where field experiments are planned to directly test the exchange mechanisms elucidated via the tested model.

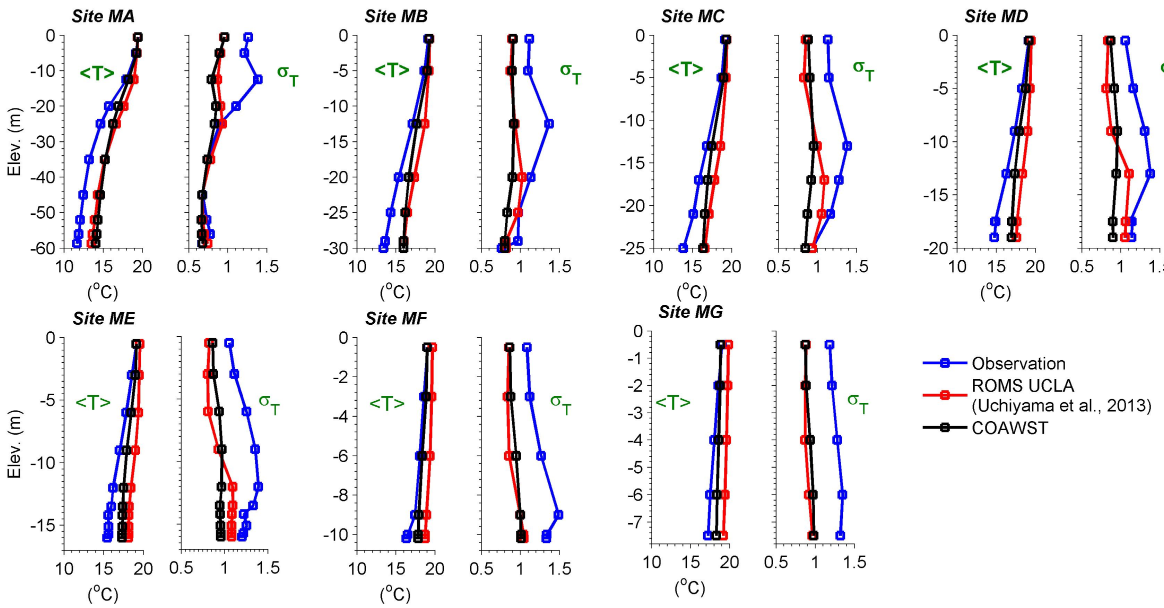

Figure 4: Mean($\langle T \rangle$) and standard deviation σ_T of vertical distribution of temperature at sites MA, MB, MC, MD, ME, MF and MG calculated using observed (blue) and simulated UCLA (red) and COAWST (black) results.

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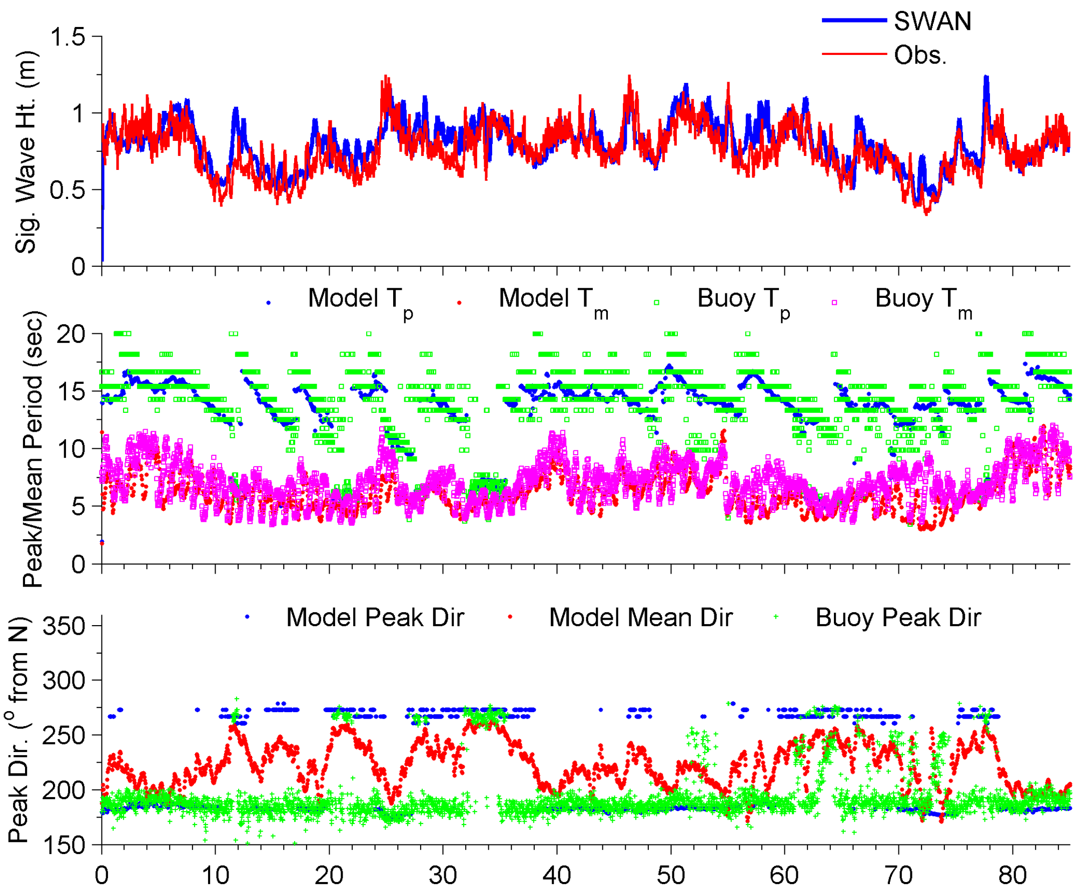

Figure 5: Comparison of modeled and 22-m depth buoy observed (top) significant wave height, (middle) peak & mean wave period, and (bottom) peak wave direction versus time

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